Pioneer Mission Support

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This article continues the description of the Pioneer F and G missions. The tracking and data acquisition support requirements are correlated with the mission characteristics. A description of the spacecraft's telecommunications and antenna subsystems is given. The CONSCAN subsystem, which has an automatic Earth-homing capability, is also delineated. The typical characteristics of the S-band telecommunications link during Jupiter encounter are depicted.

I. Introduction

The first part of this report was published in TR 32-1526, Volume II. It contained a description of the *Pioneer F* and *G* mission profile, the spacecraft system, electrical power supply, thermal control, and the structure and attitude control subsystems. Special emphasis was given on the characteristics of these missions which interface with the tracking and data acquisition functions.

This article describes both the telecommunications subsystem and the antenna system of the *Pioneer F* and *G* spacecraft. In addition, a description of the CONSCAN subsystem is given. This automatic spacecraft capability will precess the spacecraft's spin axis toward the Earth to line up the spacecraft's high-gain antenna axis to assure optimum telecommunications link performance.

II. *Pioneer F* and *G* Telecommunications Subsystem

The telecommunications subsystem performs a two-way function. The receiver portion of this subsystem maintains the telecommunications uplink with the transmitter of an Earth-based Deep Space Station; the transmitter portion sends spacecraft-originated signals in the form of a downlink toward the receiver of a Deep Space Station. Both the spacecraft receiver and transmitter can operate in a cascaded, coherent mode, thus making the extraction of the two-way doppler frequency shift possible at a Deep Space Station. This doppler frequency shift is proportional with the radial velocity between the spacecraft and the Earth-based tracking station. The time varying doppler frequency information is used to determine the spacecraft's trajectory and its space position versus time. The same doppler information is also used to generate *a priori* type frequency and antenna angle predictions necessary to make future spacecraft signal acquisition possible. The Automatic Gain Control (AGC) voltage output of the spacecraft receiver is used for spacecraft spin axis and high-gain antenna axis orientation determination and control. The rotational motion of the spin stabilized spacecraft is used to generate a conical scan AGC signal. In this mode the spacecraft antenna main lobe is offset from the antenna axis to generate a conical scan. Both *Pioneer F* and *G* spacecraft will use the standard DSN S-band carrier frequencies and will operate on channels 6 and 7 of the DSN frequency bands. The S-band Earth/spacecraft uplink will operate on the PCM/PSK/PM modulation format; the spacecraft/Earth downlink will use a single subcarrier PCM/PSK/PM modulation scheme.

Figure 1 shows a block diagram of the telecommunications subsystem. Redundant spacecraft receivers, transmitter drivers, and traveling-wave-tube amplifiers are used. In addition, redundant power supplies are also employed to ensure the highest reliability of this vital subsystem. Either spacecraft receiver or power amplifier can be connected through coaxial switches and diplexers to the spacecraft's two antenna subsystems. One of the spacecraft receivers is always connected to each of the two spacecraft antenna systems. Either receiver is automatically capable of providing a phase-coherent signal to one of the transmitter drivers whenever a spacecraft receiver is locked to an uplink signal. This coherent mode can be inhibited by command. The transmitter frequency is controlled by an auxiliary oscillator whenever the spacecraft receiver is not locked to a DSN uplink signal. The redundant traveling-wave-tube amplifiers deliver 8 watts total power to the antennas. During the early part of the mission and during maneuvers, a medium-gain/omni antenna combination is used. The omni antenna is located aft of the spacecraft and is connected via a coupler to a medium-gain antenna mounted on the antenna feed tripod of the high-gain antenna. A 2.75-meter-diameter solid parabolic antenna dish which fits into the shroud of the launch vehicle is the reflector of the high-gain antenna. This dish is illuminated with a circular polarized antenna feed. The high-gain antenna produces a maximum gain of approximately 33 dB and the half-power beamwidth is about 3.5 degrees. The forward-facing medium-gain cone antenna provides a maximum effective gain of about 12 dB and a beamwidth of 32 degrees at the half-power point. The rearward-facing omni antenna is a logarithmic conical spiral having an effective gain greater than -5 dB over the aft hemisphere of the spacecraft. Since the medium-gain and omni antennas are fed from the same power source using a coupler, an interference zone exists between the forward and aft patterns.

The spacecraft/antenna configuration is displayed in Fig. 2. The medium-gain antenna located on the top of the high-gain antenna tripod is mechanically offset from the spin axis by approximately 9 deg. This offset is necessary to generate in the spacecraft receiver an AGC voltage variation which has a somewhat distorted sinusoidal pattern if the spacecraft axis is not in line with the direction of an Earth-based Deep Space Station. The conical scan offset of the medium-gain horn antenna is mechanically fixed and cannot be changed during the flight. In contrast, the feed mechanism of the high-gain spacecraft antenna can be moved mechanically by means of an electro-thermal actuator. This device can place the antenna feed in two extreme positions. In the so-called offset position, the feed is moved out from the center of the antenna, and, therefore, the main lobe of the high-gain subsystem has an angular offset against the antenna axis and spacecraft spin axis. It should be noted that because of certain thermal equilibrium constraints of the antenna feed, the high-gain antenna of the spacecraft will operate during the first 90 days of the flight in the conical scan type offset position and the antenna feed actuator can only be commanded in to the center position after this time. Therefore, the spacecraft high-gain antenna signal (both ways) will be exposed for the first 90 days to a variation of the signal amplitude during each spacecraft revolution and at each 12-second period when the spacecraft spin axis is not lined up completely in the direction of the Earth.

There is an approximate 20-cm (8-inch) offset between the electrical axis of the high-gain antenna and the spin axis of the spacecraft. During launch operations the two RTGs, including their supporting rods, are moved toward the center of the spacecraft below the high-gain antenna, and the magnetometer boom is also folded up and located at the opposite of the two RTGs. In this configuration the spacecraft is fully balanced toward the *Z*-axis and will rotate during the first stage burning for stabilization purposes at about 60 rev/min. After spacecraft separation, an automatic on-board sequencer releases the magnetometer boom, and the supports of the RTGs, which move out from the spacecraft by means of centrifugal force, are applied upon them. After the RTGs are deployed, the spacecraft spin axis line moves away from the original center point of the high-gain antenna system toward the minus *X*-axis. The spin axis will remain approximately 20 cm (8 inches) from the high-gain antenna axis during the flight. This distance can vary slightly depending upon the fuel level in the hydrazine tank.

The polar radiation patterns of the medium-gain/omni and high-gain antenna are shown in Fig. 3. This radiation pattern indicates that there is a fringe zone between the omni and medium-gain antenna patterns because both antennas are fed from the same transmitter. Since the fringe patterns have a tilt toward the spin axis, it is expected that, during so-called spacecraft turn-around maneuvers, DSN will have difficulty in maintaining a useful telecommunications link between the spacecraft and the Deep Space Stations. The high-gain antenna pattern also shows the first order side lobes which are approximately 9 degrees from the main lobe.

III. CONSCAN Subsystem

The CONSCAN subsystem logic is a signal processor which conditions the amplitude-modulated AGC signal produced in the spacecraft receiver by the scanning motion of the offset antenna pattern, and extracts a phase reference for generation of a thruster firing signal. Figure 4 shows that the antenna lobe gain varies during the spin between positions A and B. During one 12-second spin period, the amplitude-modulated AGC signal describes one cycle of a sinewave. The positive going zero crossing of the sinewave is determined by a phase estimator which automatically fires two precession thrusters. A signal-to-noise ratio threshold detector, which is part of the CONSCAN processor, terminates the automatic thruster firing. This occurs when the amplitude modulation index of the CONSCAN signal has dropped to a point where the phase estimator cannot determine the positive going zero crossing to an acceptable accuracy. The spacecraft precession thrusters fire once per three revolutions. The integration time within the phase estimator is two revolutions. The automatic CONSCAN precession is generally initiated by a command sent from the *Pioneer F* Mission Support Area by the *Pioneer* Missions Operations Team.

Looking from the spacecraft, Earth will appear on the star sphere as a bright star. The spacecraft spin axis trajectory will describe a random walk-type spiral when the following conditions are exemplified (Fig. 5): The high-gain antenna together with the spacecraft spin axis points away from the Earth by 2.2 degrees, and the phase estimation has a constant 30-degree phase error and a signal-to-noise ratio of 10 dB. In this homing mode, the spin and antenna axes will move up to the 0.3-degree target dead zone. At this zone, the signal-to-noise ratio of the phase estimator will degrade to a level where the phase determination is not now possible. The small circles shown on the spin axis trajectory will be caused by circular movement of the spacecraft spin axis wobble. As the spacecraft spin axis reaches the CONSCAN dead zone, the threshold detector disconnects the automatic operation and the automatic CONSCAN maneuver is completed. Because of the continuous changes between the Earth and the spacecraft's relative locations, this maneuver must be repeated approximately every 3 to 4 days during the early part of the mission and every week during the time that the spacecraft travels at a Jupiter distance.

Because of signal amplitude versus noise constraints of the spacecraft's CONSCAN subsystem, the *Pioneer* Project requires that the amplitude stability of the effective radiated power transmitted by the Deep Space Stations should be within 0.1 dB peak-to-peak about the spacecraft's spin frequency.

DSN has already developed techniques to check the amplitude stability of the effective radiated power of the uplink signal, and has verified that the capability exists as required by the *Pioneer* Project for CONSCAN support. Development work in this area was conducted at DSS 71 and the verification tests were performed at DSSs 11 and 12. The best technique applied provided an upper bound measurement of the RF amplitude instability due to the combined effects of the transmitter power variations and antenna pointing errors. Using this technique, no new station hardware is required. The outputs of software analysis programs will give the assurance that the Deep Space Stations are ready for *Pioneer F* CONSCAN operations.

It should be mentioned that the spacecraft's CONSCAN processor cannot distinguish between RF amplitude variations due to the spacecraft's aiming errors and those due to fluctuations in the DSIF effective radiated power. Therefore, the use of the DSN uplink signal as a beacon signal required the re-evaluation of the ERP variations at the Deep Space Stations.

The small amplitude variations of the transmitter power were monitored with a crystal detector and with the aid of a frequency translator and the DSIF S-band receiver. The antenna pointing was evaluated using a DSS ground receiver's AGC output while tracking ALSEP 1, the Lunar Scientific Package. The assumption was made that the instability of the uplink signal amplitude due to antenna pointing errors is almost identical to that of the downlink signal.

The ERP variations detected by a synchronous AGC detector were recorded on a digital tape and analyzed off line. In addition, a power spectrum type frequency analysis was also made to obtain the data in the frequency domain.

The analysis of the data shows that the ERP variation of the DSS 11 uplink was in the vicinity of 0.0355 dB rms within the frequency response of CONSCAN. No periodic component was observable in this bandpass.

IV. CONSCAN Backup Modes

To obtain near optimum data return from the *Pioneer F* and *G* spacecraft, the Mission Operations Team of the flight project is required to make continuous plans to assure that the high-gain antenna points toward Earth during all phases of the mission. Since the CONSCAN subsystem developed for these third generation *Pioneer* missions is the first space application of an Earth-seeking automatic device, the flight project elected to develop backup modes to be used in the case of a possible degradation of the CONSCAN subsystem. Four basic backup modes are planned and certain specific requirements were generated in order to assure a successful backup operational capability.

A. Ground-Processed Uplink CONSCAN

The first of the CONSCAN backup modes is the ground-processed uplink CONSCAN. If the CONSCAN processor is inoperable, but the Sun or star sensor and the high-gain antenna offset mechanism is working, the Project plans to obtain the telemetered amplitude and phase information of the spacecraft's CONSCAN signal relative to the roll index pulse generated by the Sun or star sensor. In this mode DSN will furnish real-time spacecraft telemetry to the Missions Operations Team, and the Project will compute the roll index pulse versus CONSCAN zero crossing angle. This information will be transmitted via commands to the spacecraft and stored in the Program Storage and Execution module. The module will then fire the precession thrusters. The spin axis of the spacecraft will precess in this mode on a rhumb line. Figure 6 shows that if an Earth-based vehicle moves between two points, using a constant bearing angle versus north, the vehicle's trajectory will describe a rhumb line.

B. Ground-Processed Downlink CONSCAN

The second CONSCAN backup mode is the ground-precessed downlink CONSCAN. The spacecraft spin axis can be precessed in this mode in case the star and Sun sensors are inoperative and the high-gain antenna is in the CONSCAN offset mode. To assist the Project team in firing the precession thrusters in the proper time, DSN is required to assist the Project in the measurement of the light round-trip time. The Project will send a command to switch the telemetry format of the spacecraft. After the format change has been received by DSN, the light round-trip time can be established to an accuracy of 0.1 second. DSN plans to hold the command and telemetry systems timing accurate to 10 ms GMT. To make the ground precessed downlink CONSCAN possible, DSN also plans to transmit, via the TCD of the DSS, ten DSN S-band receiver AGC samples per second to the SFOF. This information will be used by the Project to establish a downlink CONSCAN signal in the Mission Support Area. DSN will also provide a capability to transmit command words to a transmission execution accuracy of 0.1 second in Greenwich Mean Time. With DSN's assistance the Project will have a capability to fire spin axis torquing thrusters at a predetermined roll position of the spacecraft. The roll angle position uncertainty will be in the vicinity of 3 degrees, equivalent to a thruster firing timing error of 0.1 second. The success of such a maneuver will be verified by the downlink carrier power level measurements made at the DSS and comparing them with the predicted values.

C. Dead Reckoning

Dead reckoning can also be used as a CONSCAN backup. This method can be applied if the CONSCAN processor of the spacecraft and the high-gain antenna offset are inoperable, and if the Programmed Storage and Execution board is still working. In this backup mode, the Project plans to follow the following procedure: The spacecraft's spin axis will be torqued in an open-loop mode in a transfer plane to detect and validate the peak of the antenna main lobe. In addition, once this peak is established the spin axis will also be torqued in a new plane perpendicular to the previous plane to detect and validate the improved peak of the antenna main lobe. If necessary, the spin axis can be torqued further to arrive at the opposite −3 dB point. To make a dead-reckoning maneuver possible, the Project requires that the relative downlink carrier power (AGC) measurements do not drift more than 0.125 dB. These AGC measurements will be transferred from the Deep Space Stations to the Mission Support Area at the SFOF.

Project plans to plot the resultant antenna pattern using display devices provided by DSN. Figure 7 depicts the correlation of spin axis pointing versus high-gain antenna patterns observed during a typical dead-reckoning maneuver.

D. Search Mode

The fourth CONSCAN backup mode is the search mode. If the star and Sun sensor, the Programmed Storage and Execution board, and the Antenna Offset are inoperable, the search mode maneuver can be applied to point the spacecraft high-gain antenna toward Earth. To make this possible, DSN will have a timed command capability accurate to 0.1 second in GMT. To operate the search mode, the Project will establish and verify the two-way light round-trip time by sending a timed command to the spacecraft and receive a telemetry format change. After the spin period is also established, the Project will send real-time thruster commands in a search pattern. The plotting of a high-gain antenna pattern will be used to determine the peak of the pattern, thus analyzing the results of the torquing precession maneuvers. It should be noted that the hydrazine fuel consumption in a search mode can be four times as high as the fuel needed to operate in the automatic CONSCAN mode.

V. Signatures of the Telecommunications Link

Since *Pioneers F* and *G* are using the telecommunications link for spacecraft spin axis attitude determination and control, the rotating antennas can add amplitude and phase signatures to the telecommunications downlink. The amplitude signatures are caused by the following factors:

(1) The rotating antennas in the offset CONSCAN mode can vary the S-band downlink amplitude from zero up to 10 dB during every 12-second period. The amplitude of this variation is a function of the antenna axis attitude toward Earth. If the antenna axis points exactly toward the Earth, the amplitude variation is almost zero, but, if the spacecraft high-gain antenna axis is off from the Earth direction by 2 degrees, the amplitude of the downlink can vary from zero to 10 dB during each spacecraft revolution.

(2) The spacecraft and DSN antennas are circularly polarized. The mutual polarization ellipticity between the *Pioneer F* spacecraft high-gain antenna and the DSN Earth-based antenna can cause an amplitude variation of 0.5 dB. This variation can be detected by DSN as a periodic ripple of the downlink signal amplitude. This variation occurs at the double value of the spacecraft spin rate and has a period of approximately 6 seconds.

(3) An additional amplitude variation is also caused by spacecraft wobble. Every torquing pulse causes a wobble motion of the spacecraft spin axis which is gradually damped out by special devices carried on board the spacecraft. The signal amplitude variations caused by wobble can be as high as 0.5 dB. This variation occurs at the resultant wobble frequency.

Besides the amplitude signatures, certain phase signatures are also the by products of rotating spacecraft antennas. The phase signatures can be described in two groups:

(1) The S-band downlink carrier can be exposed to phase variations caused by the spacecraft antenna spin axis offset of approximately 8″ and by antenna alignment uncertainties. Radial movements from $\pm 0.01''$ up to $\pm 1.4''$ can be expected. These variations continuously affect the downlink doppler frequency, but because of their periodic nature, they can be filtered out from the doppler solution and will not upset the accuracy of trajectory determination.

(2) Because of the mechanical rotation of the spacecraft antenna versus the fixed Earth-based DSS antenna, the two-way precision doppler counter of DSN loses approximately 2.1 doppler cycles during each spacecraft revolution. The loss of these doppler cycles can adversely affect the accuracy of trajectory determination. The Project plans to determine the spin rate history of the spacecraft using telemetry data and will generate a time history of the lost doppler cycles for trajectory determination corrections.

It should be pointed out that the described amplitude and phase signatures will not affect the performance or efficiency of ground-based hardware or software of the DSN, but will affect the operational capabilities of the spacecraft downlink especially when the amplitude variations are above 1 dB.

The *Pioneer* utilization of the two-way S-band telecommunications link can be summarized as follows: The coherent S-band carrier uplink radiated by DSN will be used in the PCM/PSK/PM mode for commanding purposes. The uplink signal will also be used by the spacecraft for automatic CONSCAN operation, thus making possible an automatic spin axis attitude control. Further use of the uplink will be the transmitting of Project-initiated timed commands in the CONSCAN backup modes. These commands will torque the spin axis attitude by ground-based control. The S-band coherent downlink signal transmitted by the spacecraft will be received by DSN. Ground-based equipment will detect the downlink carrier in a synchronous mode and one subcarrier operating in a PCM/PSK/PM mode will transfer telemetry data from the spacecraft to DSN. This function is necessary to provide the Project science and engineering telemetry data collected from the spacecraft. DSN will also provide means for the Project control team to determine the antenna pattern of the spacecraft and by detecting the downlink amplitude variations caused by spacecraft spin modulation. Both measurements will be used by the Project for spacecraft spin attitude control. Since the S-band uplink and downlink carrier is coherent, DSN extracts the doppler frequency shift which is proportional to the range rate between the ground-based station and the spacecraft. This radiometric tracking information will be used by the Project for spacecraft trajector determination.

Figures 8, 9, and 10 show typical power budgets of the S-band downlink carrier, subcarrier and uplink carrier during *Pioneer F* Jupiter encounter. The downlink carrier power performance margin referenced to a 6-dB signal-to-noise ratio threshold in the carrier tracking loop is 11.1 dB. If the spacecraft would operate in the uncoded mode at Jupiter, the telemetry bit rate would be 512 bps; the telemetry bit error rate would be one error in a thousand detected bits. Since the Project plans to operate these spacecraft most of the time in the convolutional coded mode, an error-free bit rate of 1,024 bps can be predicted assuming a coding gain of 3.8 dB. If the 64-meter DSN antenna is used with a nominal 20-kW output in the uplink, a 26-dB performance margin to threshold can be expected in the spacecraft receiver. The given performance is based upon the assumption that the spacecraft high-gain antenna points to the Earth and that the spacecraft telecommunications subsystem would operate from the Earth to Jupiter for almost two years without any detectable deterioration. With the 26-meter antenna Deep Space Stations, a Jupiter flyby telemetry rate would be 64 bps in the convolutional coded mode.

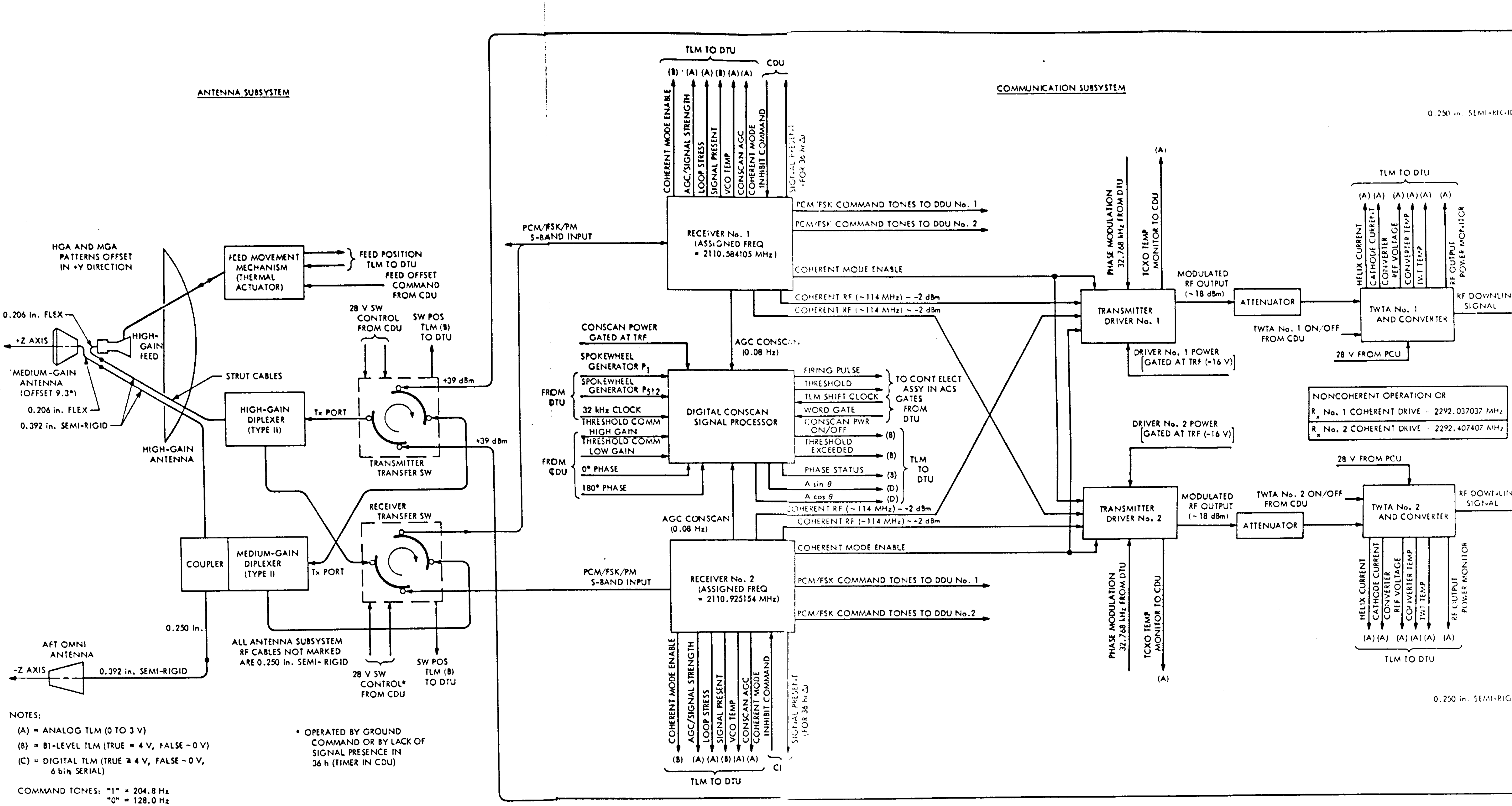


Fig. 1. ***Pioneer F*** **and G antenna and communication subsystems**

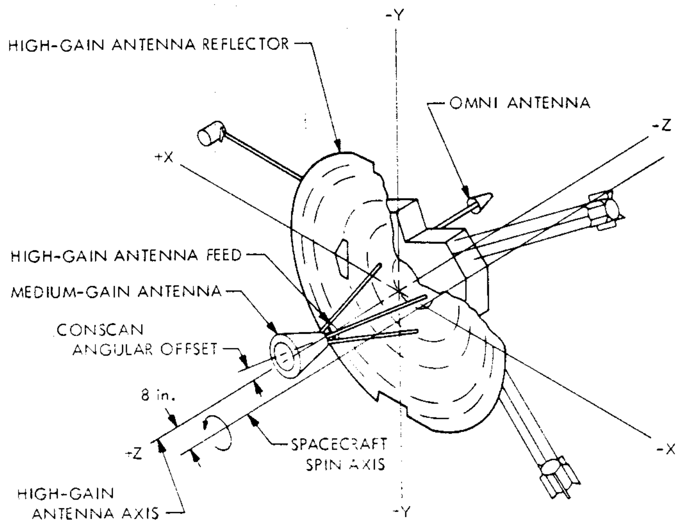


Fig. 2. *Pioneer F* and G spacecraft/antenna configuration

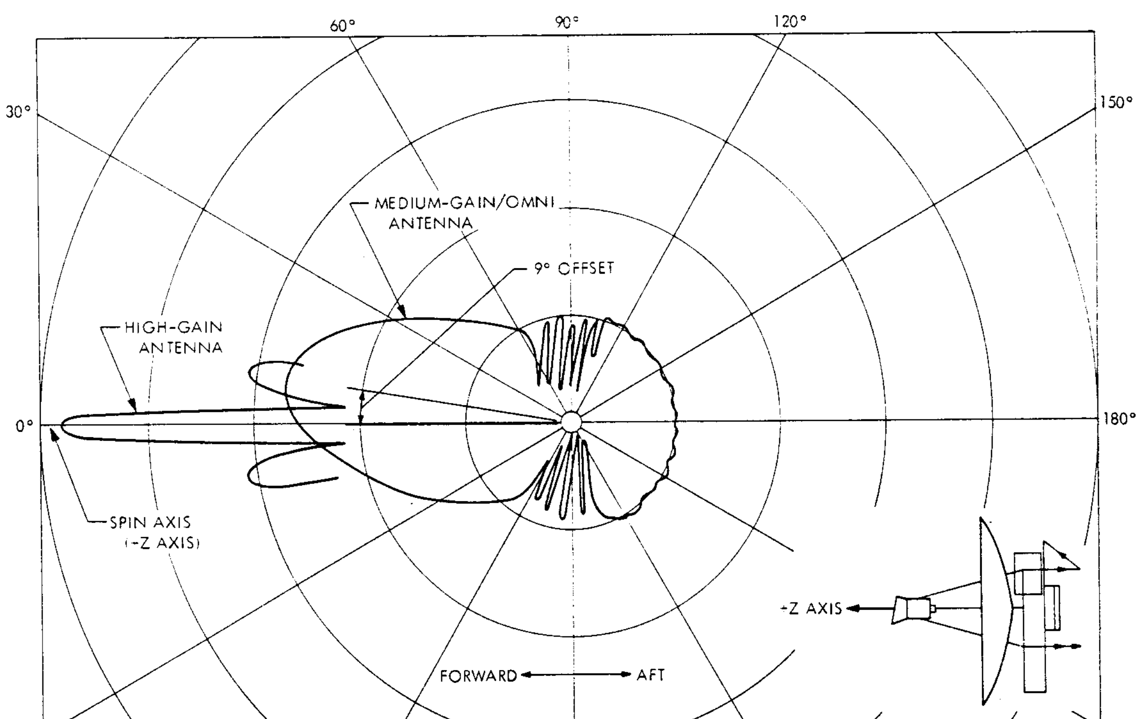


Fig. 3. Polar radiation patterns for medium-gain/omni and high-gain antennas

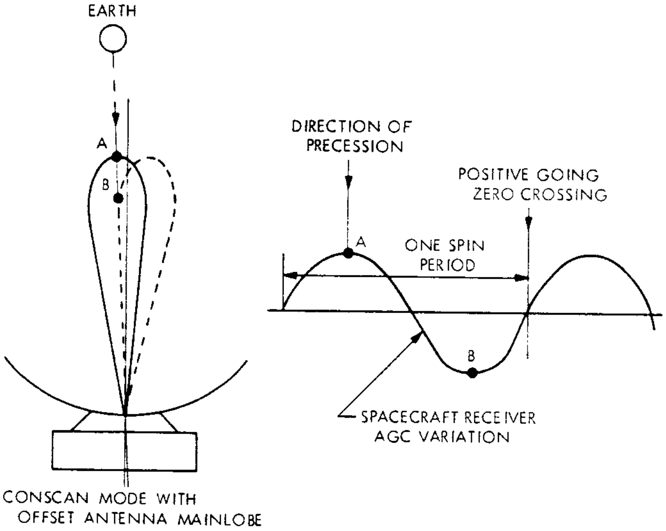


Fig. 4. CONSCAN

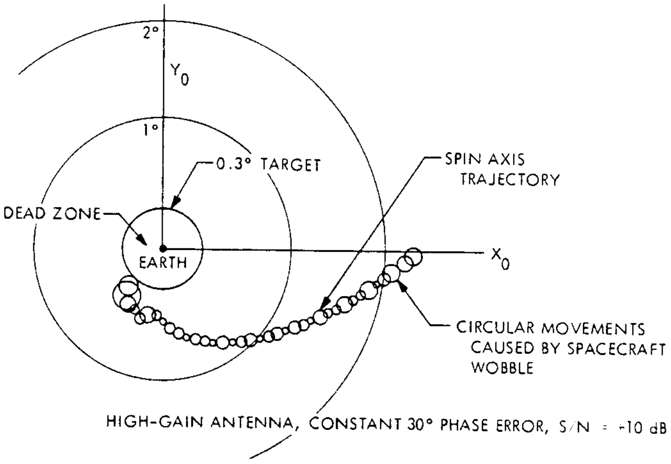


Fig. 5. CONSCAN closed-loop precession maneuver

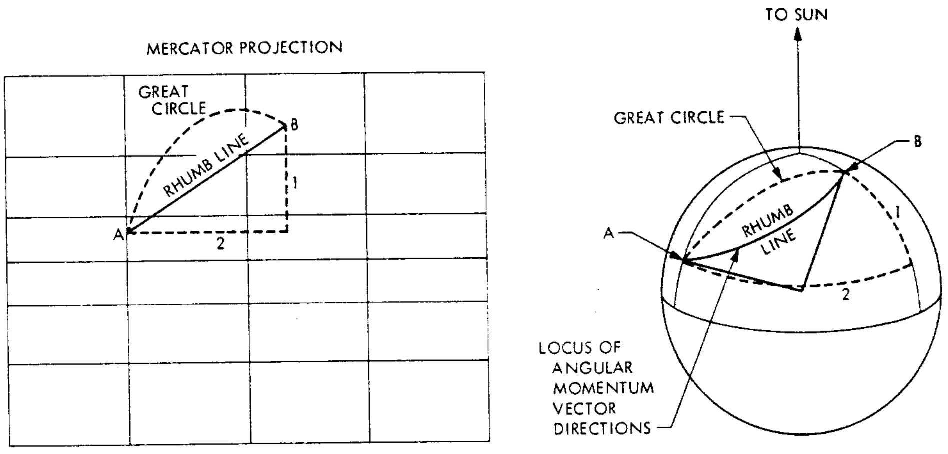
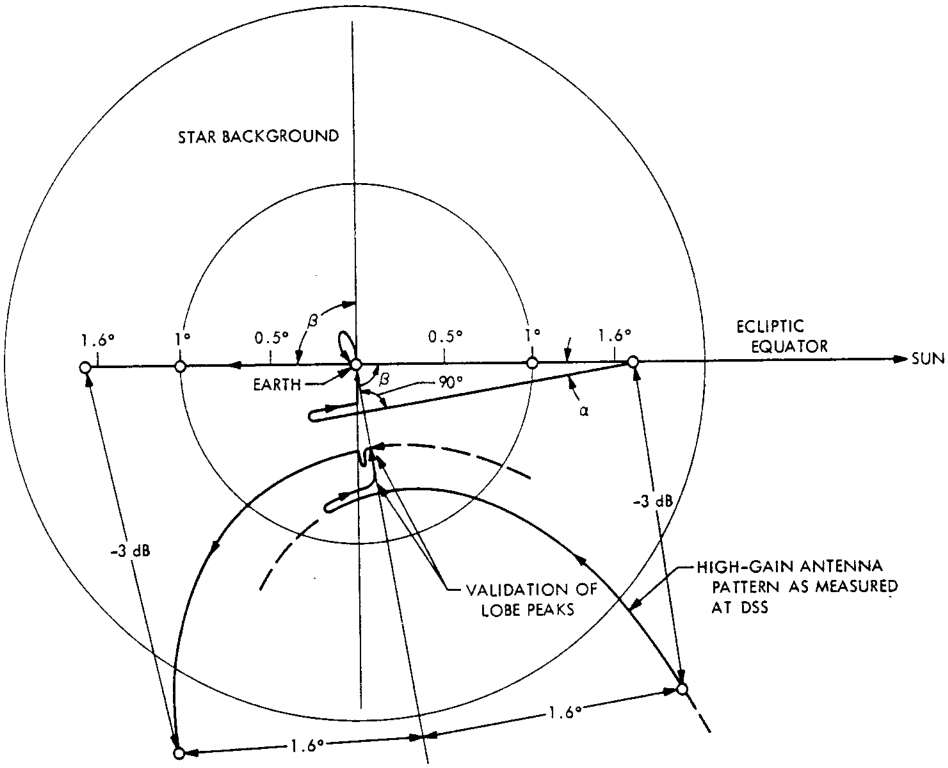


Fig. 6. Open-loop precession maneuver



α = CONSTANT ANGLE BETWEEN ROLL INDEX PULSE AND PRECESSION PLANE

SPACECRAFT SPIN AXIS WILL MOVE ON A RHUMB LINE

Fig. 7. Dead-reckoning type torquing maneuver using high-gain spacecraft antenna

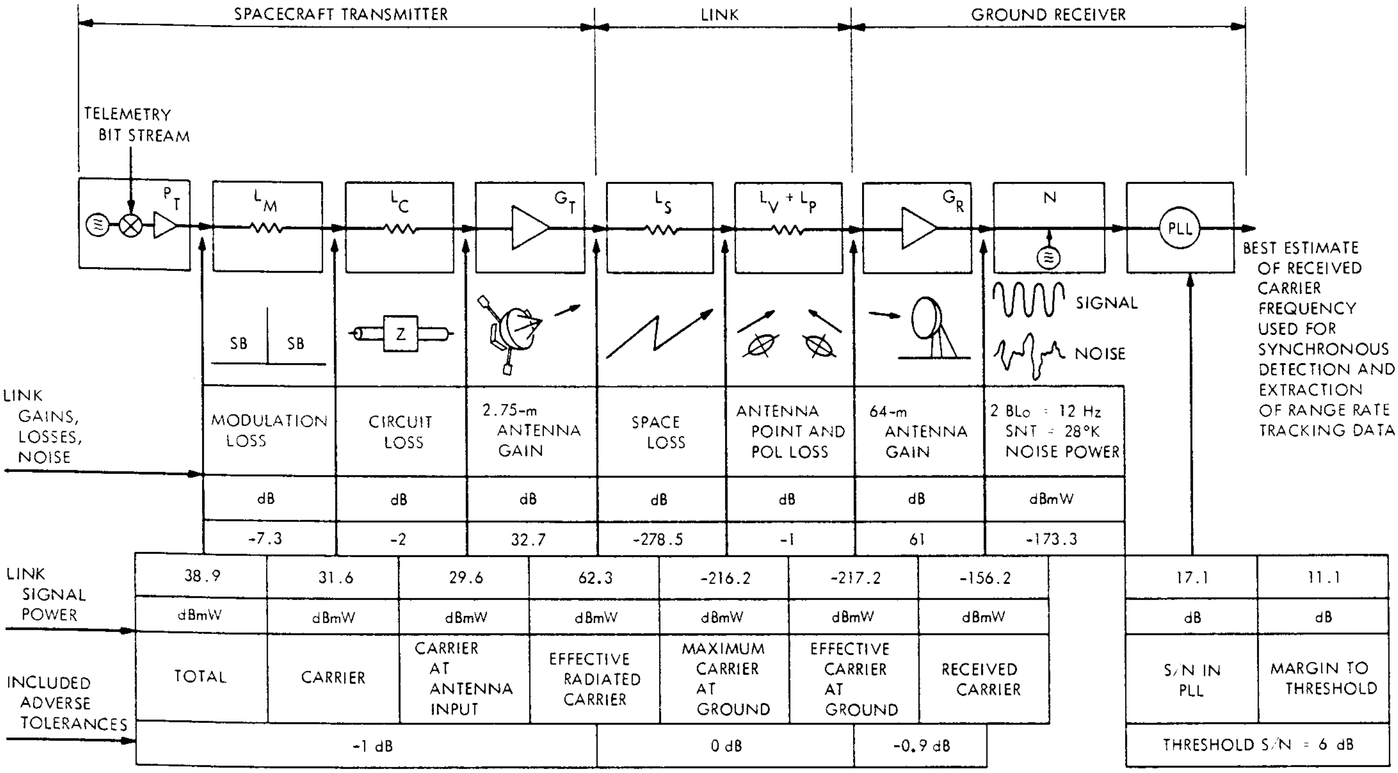


Fig. 8. *Pioneer F* Jupiter encounter downlink carrier power budget for tracking system

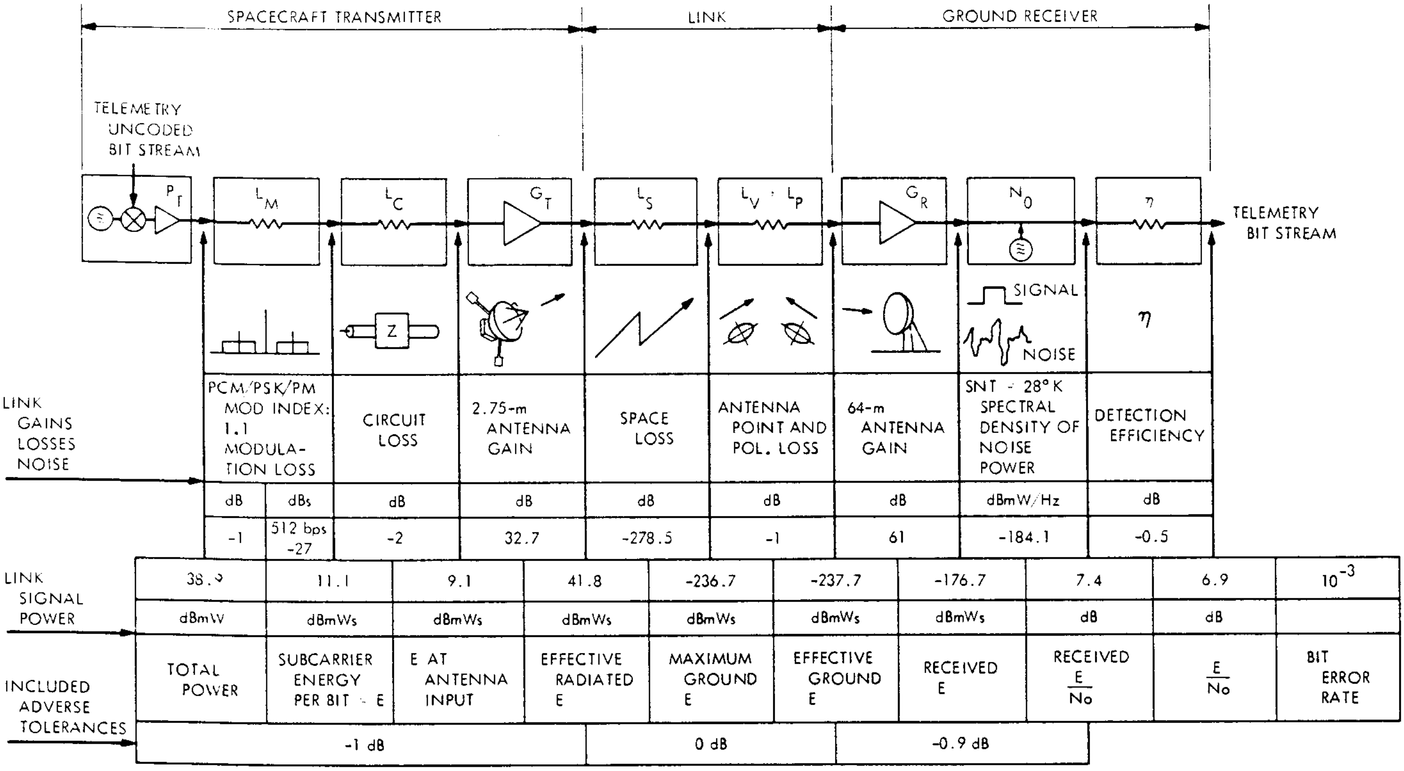


Fig. 9. *Pioneer F* Jupiter encounter downlink subcarrier power budget for telemetry system

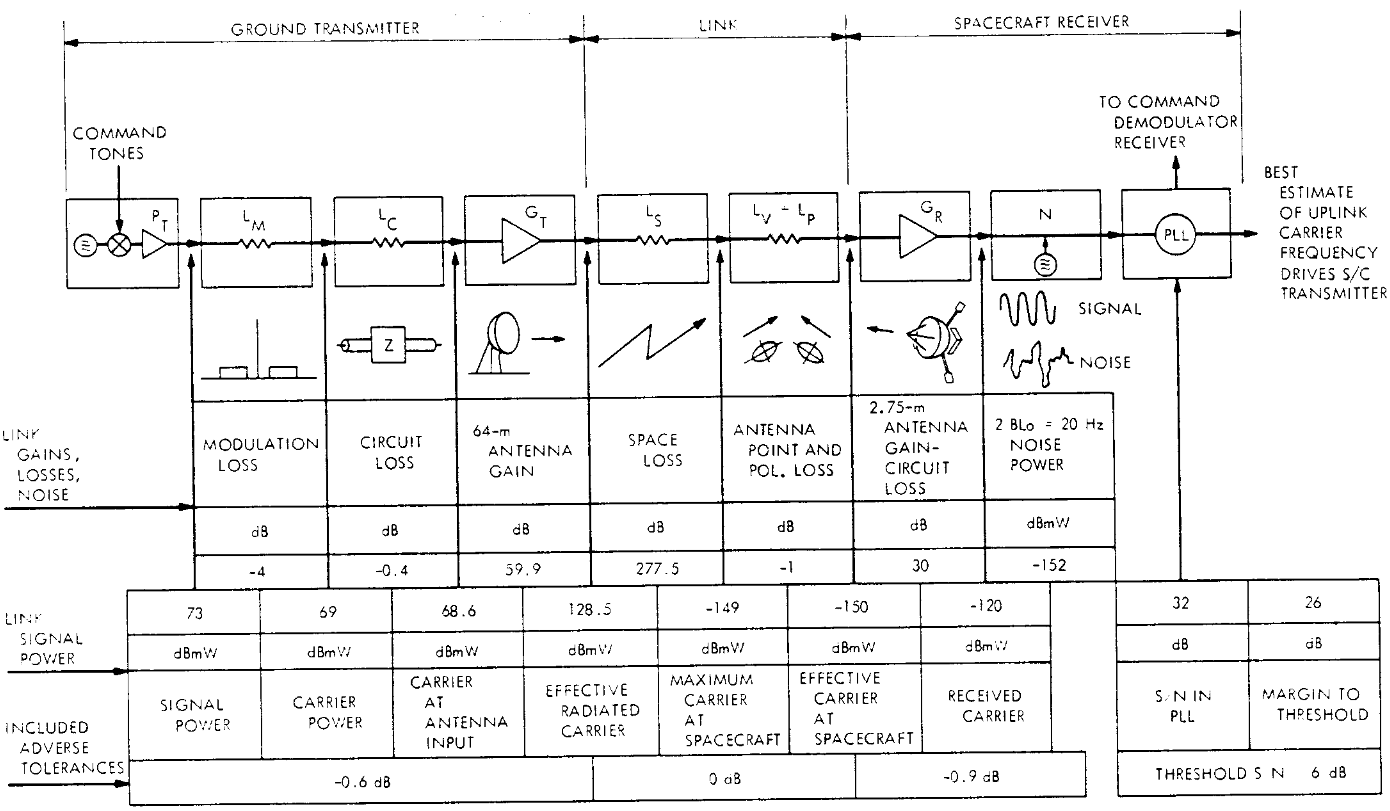


Fig. 10. *Pioneer F* Jupiter encounter uplink carrier power budget for command and tracking systems